Time reversal processing for source location in an urban environment (L)[a]

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(Received 17 June 2004; revised 8 April 2005; accepted 8 April 2005)

A simulation study is conducted to demonstrate in principle that time reversal processing can be used to locate sound sources in an outdoor urban area with many buildings. Acoustic pulse propagation in this environment is simulated using a two-dimensional finite difference time domain (FDTD) computation. Using the simulated time traces from only a few sensors and back propagating them with the FDTD model, the sound energy refocuses in the vicinity of the true source location. This time reversal numerical experiment confirms that using information acquired only at non-line-of-sight locations is sufficient to obtain accurate source locations in a complex urban terrain. [DOI: 10.1121/1.1925849]

PACS number(s): 43.28.En, 43.28.Js, 43.20.El, 43.50.Vt [DKW] Pages: 616–619

I. INTRODUCTION

An urban environment introduces many effects on acoustic propagation that are not present in the more idealized medium—a flat open area with finite impedance ground—that has often been used in studies of outdoor sound propagation. One of the major changes is the effect of buildings that act as obstacles to acoustic wave propagation and introduce multiple propagation paths, reflections, diffractions, and scattering into the propagation.

Acoustic sensors can be used to locate noise sources,[1–4] and because acoustic waves can diffract around obstacles, these sensors can potentially locate sources even when they are not directly in view of the source. (Sensors in this non-line-of-sight situation are called NLOS sensors, and those in view of the source LOS sensors.) These NLOS situations may be caused by ground topography[5] (hills) or by other obstacles like buildings.

Traditional methods of sound source location, including various beamforming or triangulation algorithms, rely on an accurate determination of the azimuthal direction of arrival of the acoustic waves. These methods may work in a NLOS situation if the acoustic wave arrival direction is unaffected by the obstacles, for example when a wave propagates over a broad hill. However, the methods will give erroneous results if the azimuthal direction of the wave arrival is different from the source direction, a situation that often occurs in both LOS and NLOS situations in an urban area with buildings present.

A method known as time reversal processing has demonstrated the ability to focus acoustic waves at the original source location in highly reverberant or scattering environments.[6–8] Relying on the time symmetry of the wave equation, the method reverses the signatures' time sequence and rebroadcasts them from the sensor locations. Remarkably, the signals propagate back through the medium and ultimately reconverge at the original source location. This method is often applied in the physical medium itself,[6,9] for example to focus waves on the stone in lithotripsy[10] or remove the reverberation in underwater communication.[11] Investigations of the time reversal method conducted using numerical models, as will be done in this paper, is less common.[6,12,13]

In this paper, time reversal processing is applied to acoustic source location in a small urban or suburban area containing a number of closely spaced buildings. The goal is to demonstrate that source location in this complex propagation environment is feasible using NLOS sensors. The finite difference method that is used to simulate acoustic propagation in the urban area is briefly discussed in Sec. II. Then, the time reversal processing method is described and is shown to provide source locations in this environment using only NLOS sensors.

[a]An earlier version of this work was presented in L. Liu and D. G. Albert, "Time reversal for source detection in urban environment," at the 147th Meeting of the Acoustical Society of America, New York, May 2004 (J. Acoust. Soc. Am. **115**, 2596).
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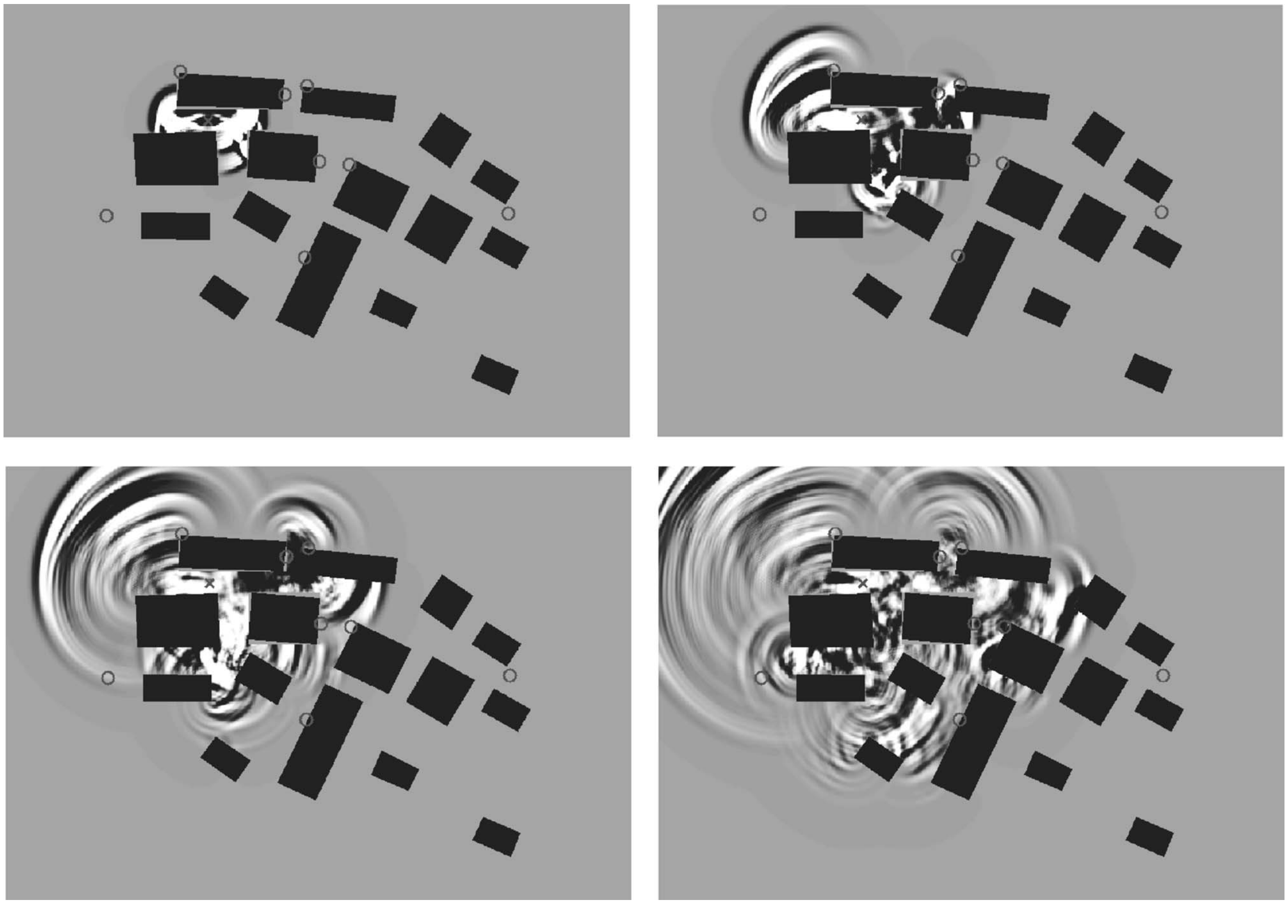

FIG. 1. Calculated acoustic pulse propagation in an urban area with 15 buildings. The area shown is 200×140 m and the building geometry is based on a full-scale artificial training village. Snapshots of the acoustic pressure are shown every 50 ms. The source was an explosion wave form located between two of the buildings and marked with an "*x*." Circles are acoustic sensor locations that will be used in the time reversal processing. (Positive pressure is black, negative pressure is white.)

II. FINITE DIFFERENCE TIME DOMAIN (FDTD) PROPAGATION MODELING

While acoustic propagation in urban areas has been studied for a long time,[14] and ray tracing or other methods for predicting sound levels in urban areas have been developed,[15–17] it is still a topic of research interest. Some recent studies have used statistical methods to measure or model traffic noise, or diffusion approaches to predict noise levels in street canyons with complex building facades.[18–21] The approach used here differs from most previous work since it attempts to model all of the waves and interactions with buildings produced by an impulsive point source. The finite difference time domain (FDTD) propagation model applied in this paper has been discussed in detail elsewhere,[22] so only a brief summary will be given.

The finite difference method is based on the expression of acoustic propagation as a set of first-order, velocity-pressure coupled differential equations, similar to the motion and continuity expressions used by other authors.[23,24] To approximate the derivatives in the acoustic wave equation with finite differences, a staggered difference algorithm proposed by Yee[25] is used in a two-dimensional spatial domain. The marching is also staggered between the computations of the air pressure and the particle velocity in the time domain. The perfectly matched layer technique[26] was adapted for the absorption boundary condition and achieved highly effective suppression of reflections from the domain boundaries.

To reduce the computational effort and make the problem tractable on a desktop computer, the real three-dimensional world is represented by a simplified two-dimensional model. Buildings are treated as solid blocks in the calculations to speed up the geometric input to the model. Corrections for the two dimensional geometric spreading (an additional factor of $r^{-1/2}$, where r is the propagation distance) and the effect of the ground surface (an additional factor of 2, assuming a rigid ground surface and that the direct and reflected path lengths are nearly identical) are applied in the calculations. With these corrections the model yields surprisingly accurate results.[22] Because of the two-dimensional approximation, acoustic energy outside the plane of the propagation model is ignored, i.e., propagation over the top of the buildings or diffraction from upper edges is not included in the calculations.

The geometry of a full-scale artificial training village is used in the calculations. This flat area has 15 closely spaced concrete buildings arranged in a 200 by 140 m area. Field measurements conducted at this location[27] will be discussed in a later publication. The computational method described

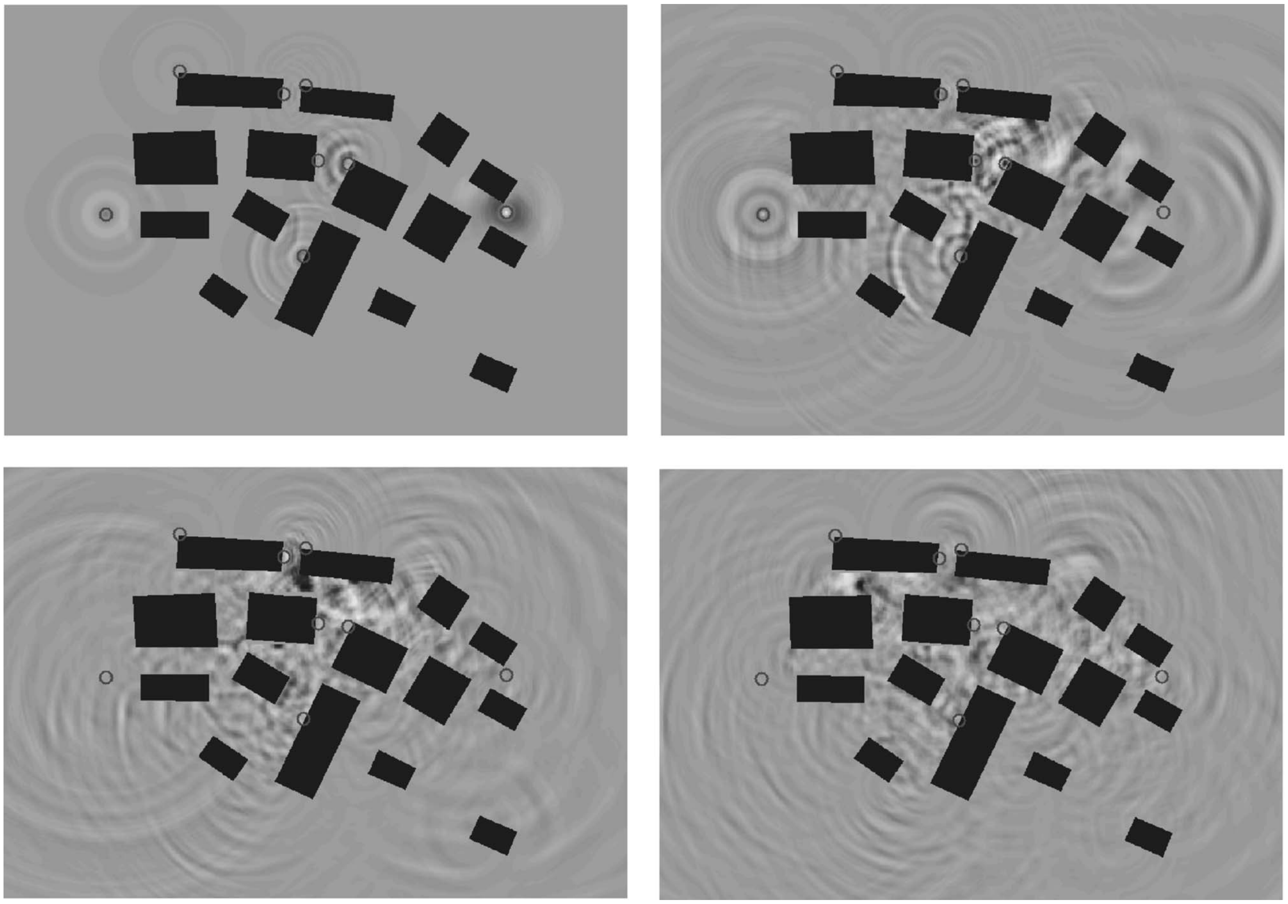

FIG. 2. Time reversal processing using eight non-line-of-sight (NLOS) sensors. The time series that had been calculated using the forward FDTD model at each of the sensor locations (circles) were time reversed and used as sources in the FDTD propagation model. Pressure wave snapshots are shown at 50, 200, 300, and 400 ms elapsed times. In the final panel (lower right), the acoustic energy has focused at the original source location (dark blob).

here should apply to any type of urban area, subject to enough computer memory and time to be able to complete the calculations.

For all of the calculations, a source function representing an explosion with a peak frequency of about 100 Hz was used. A grid spacing of 0.3 m (12 node points per wavelength) was selected, along with a time step of 0.2 ms to insure that the Courant stability criterion[24] was met. The 200 m $\times$ 140 m propagation area was divided into about 300 000 grid points. Each computation was performed in MATLAB running on a 4 GHz desktop personal computer in less than 1 h.

Figure 1 shows snapshots of the pressure wave field calculated for the small village using the FDTD method. Figure 1 shows that the many reflections, diffractions, and scattered waves caused by wave interaction with the buildings produces a very complex acoustic wave field.

III. SOURCE LOCATION USING TIME REVERSAL PROCESSING

Time reversal processing involves the following steps: First, the sound signature produced by a source is recorded at a number of sensor locations after propagation through the complex medium; next, the time series signatures are reversed in time; finally, the reversed time series are emitted from the sensor locations and propagate back through the complex medium. Because of the symmetry of the wave equation, this procedure will refocus acoustic energy at the original source location.

The time reversal steps were performed using the FDTD model for the urban situation shown in Fig. 1, and Fig. 2 shows wave field snapshots of the process using eight NLOS sensors. In the final panel, acoustic energy can be seen focusing at the original source location (shown with an x in Fig. 1). In Fig. 3, the final results of time reversal processing are compared for the same case with eight NLOS sensors, and for a case where only three NLOS sensors are used. Both cases find the correct source location, although the result is stronger for the case with eight sensors compared to the case with three sensors.

To apply the time reversal method in an actual urban area, the building locations, sensor locations, and time signatures are required. With this information the method can be applied to find unknown source locations using the FDTD model as demonstrated earlier. However, before this method could be used in practice, for example to locate gunshots in near real time, the calculation time will need to be decreased by about three orders of magnitude. In addition, further study of this technique is needed to determine the resistance of the method to errors in sensor or building locations and to ambient noise. Despite these requirements, the method could

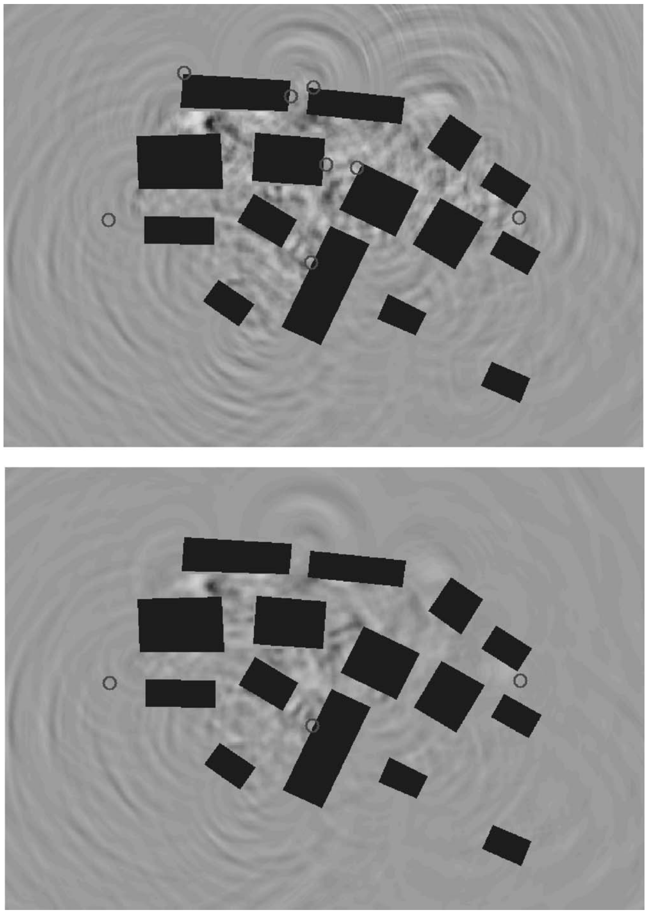

FIG. 3. Results of time reversal processing to determine the sound source location in an urban area. The top panel shows the results from eight NLOS sensors (circles), while the lower panel shows the results using only three NLOS sensors. Both give the correct source location, but the result for eight sensors is more focused and displays lower sidelobes than the result found using three sensors.

become feasible for application to a specific location with fixed and known sensor and building locations, if a precomputing strategy similar to Ref. 28 was used.

IV. CONCLUDING REMARKS

The two-dimensional finite difference time domain method has been used to calculate acoustic wave propagation in a small urban area with a number of closely spaced buildings. The simulation study presented here shows that time reversal processing on the acoustic signatures from a few non-line-of-sight sensors to determine a source location is conceptually possible.[29]

ACKNOWLEDGMENTS

The authors thank the many colleagues who have helped with this project, and the U.S. Army PM-CCS and the U.S. Army Corps of Engineers for funding this research. In addition, thanks are given to the Associate Editor, Dr. Keith Wilson, for many helpful suggestions to improve the manuscript.

[1]A. De Ciccio, "Sound ranging and locating system AN-TNS-3, used in 1950," (private communication).
[2]G. C. Carter, "Time delay estimation for passive sonar signal processing," IEEE Trans. Acoust., Speech, Signal Process. **ASSP-29**, 463–470 (1981).
[3]B. G. Ferguson, "Variability in the passive ranging of acoustic sources in air using a wavefront curvature technique," J. Acoust. Soc. Am. **108**, 1535–1554 (2000).
[4]W. R. Hahn, "Optimum signal processing for passive sonar range and bearing estimation," J. Acoust. Soc. Am. **58**, 201–207 (1975).
[5]C. You, "Non-line-of-sight sound propagation outdoors," Ph.D dissertation, *Department of Physics and Astronomy*, University of Mississippi: Oxford, MS, 1993 109 pp.
[6]A. Derode, P. Roux, and M. Fink, "Robust acoustic time reversal with high order multiple scattering," Phys. Rev. Lett. **75**, 4206–4209 (1995).
[7]M. Fink, "Time reversal of ultrasonic fields I. Basic principles," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39**, 555–566 (1992).
[8]M. Fink, "Time-reversed acoustics," Phys. Today **50**, 34–40 (1997).
[9]G. Montaldo, P. Roux, A. Derode, C. Negreira, and M. Fink, "Generation of very high pressure pulses with 1-bit time reversal in a solid waveguide," J. Acoust. Soc. Am. **110**, 2849–2857 (2001).
[10]J.-L. Thomas, F. Wu, and M. Fink, "Time reversal mirror applied to lithotripsy," Ultrason. Imaging **18**, 106–121 (1996).
[11]W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla, and D. R. Jackson, "Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirror," J. Acoust. Soc. Am. **103**, 25–40 (1998).
[12]S. R. Khosla and D. R. Dowling, "Time-reversing array retrofocusing in noisy environments," J. Acoust. Soc. Am. **109**, 538–546 (2001).
[13]P. Roux and M. Fink, "Time reversal in a waveguide: Study of the temporal and spatial focusing," J. Acoust. Soc. Am. **107**, 2418–2429 (2000).
[14]F. M. Wiener, C. I. Malme, and C. M. Gogos, "Sound propagation in urban areas," J. Acoust. Soc. Am. **37**, 738–747 (1965).
[15]K. P. Lee and H. G. Davies, "Nomogram for estimating noise propagation in urban areas," J. Acoust. Soc. Am. **57**, 1477–1480 (1975).
[16]D. J. Oldham and M. M. Radwan, "Sound propagation in city streets," Build. Acoust. **1**, 65–88 (1994).
[17]K. Heutschi, "A simple method to evaluate the increase of traffic noise emission level due to buildings, for a long straight street," Appl. Acoust. **44**, 259–274 (1995).
[18]J. Kang, "Sound propagation in street canyons: Comparison between diffusively and geometrically reflecting boundaries," J. Acoust. Soc. Am. **107**, 1394–1404 (2000).
[19]J. Picaut, L. Simon, and J. Hardy, "Sound field modeling in streets with a diffusion equation," J. Acoust. Soc. Am. **106**, 2638–2645 (1999).
[20]A. Garcia and L. J. Faus, "Statistical analysis of noise levels in urban areas," Appl. Acoust. **34**, 227–247 (1991).
[21]A. L. Brown and K. C. Lam, "Levels of ambient noise in Hong Kong," Appl. Acoust. **20**, 85–100 (1987).
[22]L. Liu and D. G. Albert, "Acoustic pulse propagation near a right-angle wall," J. Acoust. Soc. Am. (submitted).
[23]J. Virieux, "SH-wave propagation in heterogeneous media: Velocity-stress finite difference method," Geophysics **49**, 1933–1942 (1984).
[24]S. Wang, "Finite-difference time-domain approach to underwater acoustic scattering problems," J. Acoust. Soc. Am. **99**, 1924–1931 (1996).
[25]K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell″s equations in isotropic media," IEEE Trans. Antennas Propag. **14**, 302–307 (1966).
[26]J. P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves," J. Comput. Phys. **114**, 185–200 (1994).
[27]D. G. Albert and L. Liu, "Sound propagation in an urban environment I. Preliminary analysis of measurements," J. Acoust. Soc. Am. **114**, 2442 (abstract) (2003).
[28]R. K. Ing, N. Quieffin, S. Catheline, and M. Fink, "Time reversal interactive objects," J. Acoust. Soc. Am. **115**, 2589 (abstract) (2004).
[29]Movies of urban propagation and time reversal processing are available at http://www.acoustics.org/press/147th/liu-albert.html.